THERMAL INSULATING VALUE OF CELLULAR SHADES WITH AND WITHOUT SIDE SEALS

by

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ABSTRACT

The thermal insulating characteristics of two types of cellular shades, light-filtering and light-blocking, were measured under cold-weather conditions. These thermal resistance values, or R-values, were measured both with and without the side seals. These cellular shades were manufactured under the trade name Comfortex Symphony® ConforTrack™ Plus, and were double-cell shades, with 9.5 mm (3/8") cells arranged to form a double layer. The measured R-values were dramatically improved with the side seals, by a factor of 2x for the light-filtering shades and 2x-3x for the light-blocking shades. The light-blocking shades had significantly higher R-values than the light-filtering shades, but all were significantly less than the advertised values. The measured R-values decreased with decreasing outdoor temperatures.

To avoid specifying the units throughout the report, R_{SI} will be used to specify R-values in SI units of m^2 ˚C/W, and R_{US} will be used for United States units of ft^2 ˚F hr/Btu. At an outdoor temperature of -7˚C (20˚F), the R-value for the light-filtering shades without side seals was $R_{SI} = 0.10$ ($R_{US} = 0.57$), while the addition of the side seals more than doubled the R-value to $R_{SI} = 0.21$ ($R_{US} = 1.2$). For the light-blocking shades without side seals, the R-value at an outdoor temperature of -7˚C (20˚F) was $R_{SI} = 0.13$ ($R_{US} = 0.74$), while adding the side seals more than doubled this value to $R_{SI} = 0.35$ ($R_{US} = 2.0$). These values are significant relative to typical R-values for windows, so the addition of this type of shade can dramatically reduce heat losses through windows. Current building codes in colder parts of the United States require minimum window R-values (without shades) of $R_{SI} = 0.50$ ($R_{US} = 2.9$), so adding light-blocking shades with side seals can increase the effective combined minimum R-values by 70%.

A previous report showed higher R-values for insulating shades than those reported here, but errors in the analysis used in that report are documented in this report.

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

As homes are built more carefully and with thicker walls and higher insulation levels to reduce energy usage for heating and cooling, windows can be the weak link in heat losses due to their low insulation values. (Windows can also be a source of significant solar heating, which in heating-dominated climates can be important.) Heat losses through windows can be reduced by increasing the number of window panes, by using spectrally dependent coatings to reduce the thermal emissivity of the windows ("low-e") while maintaining good transparency, and by adding window coverings to reduce heat losses. Window coverings can also significantly reduce solar heat gains during times when a building must be cooled.

Concerning window coverings for reducing heat transfer through the windows, there is considerable interest in cellular shades that are based on the concept of trapping a dead air space in a honeycomb-like structure between the window and the interior of the building. In theory, this dead air space should provide a fairly effective insulation layer within the window covering, and yet the shades can be raised and the dead air space collapsed, making a compact storing device. This report examines in detail the insulating characteristics of cellular shades, and the effects on insulating characteristics of light-filtering versus light-blocking shades, and the effect of labyrinth seals along the edges of the shade to reduce air circulation.

BACKGROUND

There are standards for measuring heat transfer through windows, such as ASTM C1199 – 09e1, "Standard Test Method for Measuring the Steady-State Thermal Transmittance of Fenestration Systems Using Hot Box Methods." The National Fenestration Rating Council (NFRC) also has recommended procedures for determining heat transfer through windows such as NFRC 100-2010, "Procedure for Determining Fenestration Product U-factors.

There do not appear to be standards for measuring heat transfer rates, or their inverse, R-values, for window *coverings*. As a result, the R-values for window coverings are essentially uncontrolled, and might be exaggerated.

A report was written by Steven Winter Associates, Inc. on the same type of shades tested here, the ComforTrack^{TM} Cellular Shades, except that only the light-blocking shades were tested. This report is available at Reference 1. They report R-values of $R_{SI} = 0.16$ ($R_{US} = 0.9$) without the side seals, and $R_{SI} = 0.42$ ($R_{US} = 2.4$) in tests using older, single-pane, double-hung, wooden windows with exterior aluminum storm windows. Although the thermal resistance of the shades should be independent of the window type, they report higher R-values when the shades were tested with newer (2008), low-e, vinyl-framed, double-hung windows. In the case of the newer, low-e windows, they report R values without the side seals of $R_{SI} = 0.25$ ($R_{US} = 1.4$), and $R_{SI} = 0.77$ ($R_{US} = 4.4$) with the side seals. However, it is shown in this report that the results by Steven Winter Associates were in error and biased toward higher R-values by the approach used to process the measurements, as discussed below in the section titled Test Procedure.

In some advertising, e.g., Reference 2, even slightly higher R-values than those in the Steven Winter report are presented. Since there are no standards for measurements of thermal resistance for window coverings, advertisers appear to use a lack of restraint in coming up with R-values for their products.

EXPERIMENTAL APPARATUS

Window Shades

The window shades tested were Symphony® 9.5 mm (3/8") double-cell cellular shades with Comfortrack™ Plus side seals, and they were manufactured by Comfortex. The double-cell structure can be seen in Figure 1 below. There is a slot between the two rows of cells, and the labyrinth side seals fit into that slot. The side-sealing system is shown in Figure 2 below, and includes the plastic projection that penetrates the gap between the two rows of cells, and a Z-shaped polymer gasket that expands to fill the gap between the side of the window frame and the outer half of the shade. The overall system as installed is shown in Figure 3 and Figure 4. Note that for air to circulate around the sides of these shades, the air must penetrate the gap between the Z-shaped polymer spring material and the row of cells closer to the window in the shades, and then must penetrate the labyrinth piece that fits between the two rows of cells. This sealing system is shown in these tests to dramatically increase the insulating capabilities of these shades. The side seals are held to the frame of the windows magnetically, and are easily removable, as they were for some of the tests reported here without side seals.

The thermal insulating characteristics of two types of cellular shades, light-filtering and light-blocking, were measured under actual operating conditions. The light-blocking shades incorporated something like aluminum foil in their construction to block the light. The shade material in the light-blocking shades was stiffer than the material in the light-filtering shades, making them more difficult to lower, usually requiring manual assistance to get them all the way down.

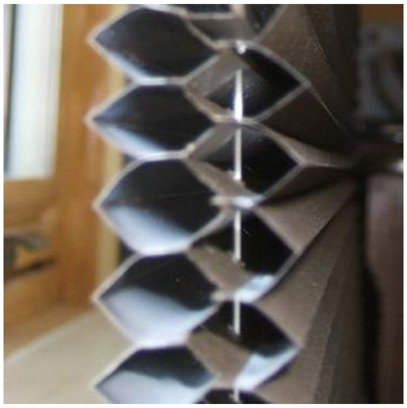

Figure 1. Side View of Double-Cell Structure of Cellular Shades. Slots for Side Seals are in Same Plane as Cord.

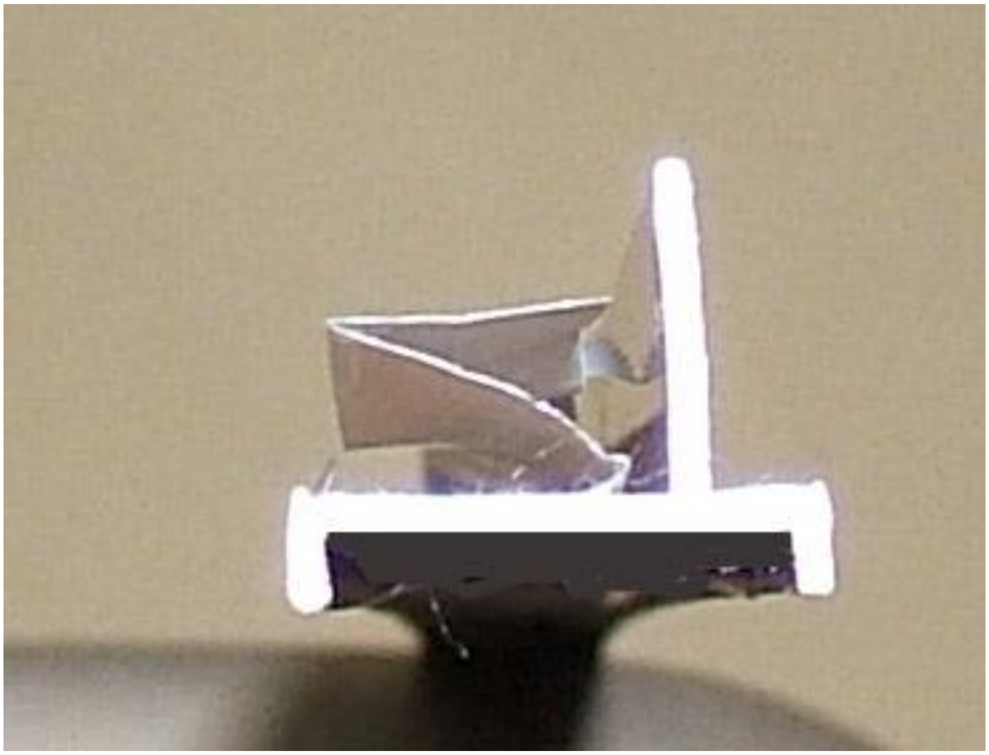

Figure 2. Side Seals of ComforTrack™ Plus System showing the Z-shaped Polymer Gasket.

Figure 3. ComforTrack™ Plus Shades with Side Seals in Place.

Figure 4. Another View of ComforTrack™ Plus Shades with Side Seals.

Windows

The windows used in the testing are important since the R-value for the shades is computed based on the R-value for the windows and the relative temperature drops across the windows and the shades. The windows used in this study were relatively new (2010) Pella Designer windows that are low-e (low infrared emissivity), triple-pane windows. Rather than having all three panes in one insulated glass unit, these windows use two panes in an insulated glass unit, and the third pane, toward the inside of the house, has its own sealing surface. This design is used to allow the inner pane to be tilted inward and optional mini-blinds to be installed between the inner pane and the outer two panes. (Mini-blinds are not a part of the windows that were tested.) Both low solar gain and high solar gain windows are installed in the house, and some of the testing was conducted on both types of windows. The low solar gain windows have a thermal conductivity specified at 1.65 W/m^2 ˚C (0.29 Btu $/ft^2$ ˚F hr), corresponding to an R-value of $R_{SI} = 0.61$ ($R_{US} = 3.4$). The thermal conductivity of the high solar gain windows is slightly higher (i.e., thermal resistance lower), being specified as 1.76 W/m^2 ˚C (0.31 Btu $/ft^2$ ˚F hr), corresponding to an R-value of $R_{SI} = 0.57$ ($R_{US}= 3.2$). The higher thermal conductivity for the high solar gain windows is due to the higher long-wavelength infrared emissivity of these windows that results from changing the coating to allow more short-wavelength infrared solar energy to enter the home.

All of the windows used for these tests were of the same size, and all measured 1.04 m (41”) W x 1.50 m (59”) H (rough opening dimensions). Five windows were used for these tests, two with low solar heat gain (#1 and #2), and three with high solar heat gain (#9, #13, and #15). The experimental results presented below use these window numbers. All windows were closed and locked for these tests. All testing was done when no sun was shining on the window being tested. Most tests were conducted early in the morning about the time that the outside temperature reached a minimum, and when the indoor, outdoor, and shade temperatures were well stabilized. Winds are typically low during this period.

Instrumentation

Temperature measurements were made with “1-wire” T-Sense™ temperature sensors obtained from iButtonLink. A sensor is shown in Figure 5. Dimensions are 44.5 mm L x 19.1 mm W x 19.1 mm H (1-3/4"L x 3/4"W x 3/4"H). The actual temperature sensor is located 9.5 mm (3/8”) from each edge of the device. These sensors can be strung together using a pair of wires in a cable and RJ45 connectors on each end of the sensors. These temperature sensors are interfaced with a personal computer through a DS1401 adapter, and OneWireViewer software is used to display and plot results.

Figure 5. T-Sense Temperature Sensor from iButtonLink. Temperature Sensor is in the Nipple on Top of Sensor in this Picture.

For all of the temperature measurements reported here, four sensors were attached to the inside of the windows, one sensor each located near the center of the top and bottom panes, and one each near the edges of the top and bottom panes, as shown in Figure 6. The sensors were mounted such that the temperature sensing elements were 9.5 mm (3/8”) toward the room side from the inner surface of the innermost glass pane (surface #6 in the standard parlance used to number window panes from outside to inside). The four readings were averaged together to get a single value for the air temperature between the window and the shade.

Figure 6. Location of the Four T-Sense™ Temperature Sensors on each Window.

Outside temperatures were computed from an average of two liquid thermometers, with their average temperature reading averaged together with a solid state temperature sensor. Inside temperatures were taken from a solid state temperature sensor located in the thermostat.

TEST PROCEDURE

The approach used to measure the thermal resistance (R-value) of the window shades was to measure air temperatures outside and inside the house, and between the windows and the shades. Then the R-values of the windows were taken as known values, and the R-values of the shades were solved for based on the temperature measurements. This approach is similar to that used by Steven Winter Associates, but the mathematical analysis was different. This approach does depend on knowing the R-values of the windows accurately, and for that reason, tests were conducted on multiple windows for each type of window shade (light-filtering and light-blocking) to average out window-to-window variability.

In agreement with the assumption made by Steven Winters Associates, the heat flow through the window and the heat flow through the shade are taken as equal. Said another way, the main heat flow is through the window and shade, and not in or out into the window frame. The heat flux density through the window is written as:

$$\dot{q}_{window} = U_{window}\,(T_{shade} - T_{out}) \qquad (1)$$

where:
$\dot{q}_{window}$=Heat flux density through window (W/m^2)
U_{window} = Thermal Conductivity of Window (W/m^2 ˚C)
T_{shade} = Air temperature between the window and the shade (˚C)
T_{out} = Outside temperature well away from the window (˚C)

Since the thermal conductivity of the windows is known (from the window specifications), and the temperatures can be measured, then the heat flux through the window can be computed. From the above section on windows, the U-value for the low solar gain windows is 1.65 W/m^2 ˚C (0.29 Btu/ft^2 ˚F h), and for the high solar gain windows is 1.76 W/m^2 ˚C (0.31 Btu/ft^2 ˚F h)

Now if the heat flux density through the window is equal to the heat flux density through the shade, then,

$$\dot{q}_{shade} = \dot{q}_{window} \qquad (2)$$

and similarly to the equation for heat flux density though the window,

$$\dot{q}_{shade} = U_{shade}\,(T_{in} - T_{shade}) \qquad (3)$$

where:
$\dot{q}_{shade}$=Heat flux density through shade (W/m^2)
U_{shade} = Thermal conductivity of shade (W/m^2 ˚C)
T_{in} = Inside temperature well away from the window and shade (˚C)
T_{shade} =Air temperature between the window and the shade (˚C)

Since by definition the thermal resistance R is the inverse of the thermal conductance U, then,

$$R_{shade} = 1/U_{shade} \qquad (4)$$

Then Eq. (3) may be rearranged using Eq. (4) as,

$$R_{shade} = \frac{(T_{in} - T_{shade})}{\dot{q}_{shade}} = \frac{(T_{in} - T_{shade})}{\dot{q}_{window}} \qquad (5)$$

and substituting for $\dot{q}_{window}$ from Eq. (1),

$$R_{shade} = \frac{(T_{in} - T_{shade})}{U_{window}\,(T_{shade} - T_{out})} = R_{window}\frac{(T_{in} - T_{shade})}{(T_{shade} - T_{out})} \qquad (6)$$

Now Eq. (6) makes sense. If the shade is highly insulating compared to the window, then most of the temperature drop will across the shade, i.e., $(T_{in} - T_{shade})$ will be large compared to $(T_{shade} - T_{out})$, and R_{shade} will be larger than R_{window} in agreement with Eq. (6).

The problem with Eq. (6) is in measuring T_{shade} that turns out to be far from uniform, as will be shown below, and cannot be measured far from the window where the temperature is out of the boundary layer. T_{in} and T_{out} may be measured far from the window/shade assembly where they are constant, but T_{shade} is necessarily defined in the small region between the window and the shade where the air temperatures are in the boundary layers for both the window and the shade, and are not constant. The problem is most clearly demonstrated by example.

Imagine a shade made of a few paperclips, or some other imaginary shade with no insulating value. The imaginary shade may be simulated by simply raising the cellular shade all the way up. Then temperature data may be recorded with the shade raised, and the thermal resistance, R_{shade}, value better be zero for the imaginary shade. However, using actual experimental data inserted into Eq. (6), the value for R_{shade} is not zero due to this boundary layer effect. The R-value computed for the imaginary shade, R_imag, is shown in Table 1 in SI units, and in Table 2 in United States units. The “shade temperatures” were measured 9.5 mm (3/8”) from the window surface of window #15 (a high solar gain window), and these temperatures were significantly lower than the indoor temperature measured away from the windows. On average, the R-values for the imaginary shade were about 10% of the R-value for the window.

Table 1. R_{SI} for Imaginary Shade Computed from Eq. (6), Column R_imag, on a Window with R_{SI} = 0.56.

Date	Avg. inside shade location (˚C)	Inside house temp. (˚C)	Outside temp. (˚C)	R_imag	Depression of window temps	(Ts-Tout) /0.9 /(Tin-Tout)	R_s
1/2/2011 8:43	16.3	19.4	-11.8	0.06	10.2%	1.0	0.00
1/2/2011 10:42	16.8	18.9	-4.1	0.06	9.0%	1.0	-0.01
1/4/2011 8:16	15.8	19.4	-13.3	0.07	11.0%	1.0	0.01
1/4/2011 9:03	16.6	19.4	-10.0	0.06	9.6%	1.0	0.00
1/4/2011 9:35	16.5	18.9	-8.3	0.05	8.7%	1.0	-0.01
1/4/2011 11:10	17.6	18.3	0.6	0.03	4.4%	1.1	-0.03
1/4/2011 18:09	16.0	18.9	-2.4	0.09	13.4%	1.0	0.02
			Average	0.06	9.5%		

Table 2. R_{US} for Imaginary Shade Computed from Eq. (6), Column R_imag, on a Window with R_{US} = 3.2.

Date	Avg. inside shade location (˚F)	Inside house temp. (˚F)	Outside temp. (˚F)	R_imag	Depression of window temps	(Ts-Tout) /0.9 /(Tin-Tout)	R_s
1/2/2011 8:43	61.3	67	10.8	0.4	10.2%	1.0	0.0
1/2/2011 10:42	62.3	66	24.7	0.3	9.0%	1.0	0.0
1/4/2011 8:16	60.5	67	8	0.4	11.0%	1.0	0.0
1/4/2011 9:03	61.9	67	14	0.3	9.6%	1.0	0.0
1/4/2011 9:35	61.8	66	17	0.3	8.7%	1.0	0.0
1/4/2011 11:10	63.6	65	33	0.1	4.4%	1.1	-0.2
1/4/2011 18:09	60.9	66	27.7	0.5	13.4%	1.0	0.1
			Average	0.34	9.5%		

The boundary layer problem is quantified in Figure 7 (in degrees Centigrade) and Figure 8 (in degrees Fahrenheit). Note the position of the shade relative to the lower window. The total gap between the inner window surface and the shade is about 30 mm (1.2"), and there are strong temperature gradients when no shade is present out to well beyond 100 mm (4"). Therefore, there is a temperature differential between the shade temperature and the inside house temperature even with no shade present. As shown in Table 1 (and Table 2 in United States units), the temperature differential between the outdoor and shade temperature was about 9.5% lower than temperature differential between the outdoor and the indoor temperatures. The heat conduction through the window should be computed based on the differential between the outdoor and indoor temperatures. When the shade is present, only the shade temperature is available to compute the differential temperature. An approximate correction when using the shade temperature to represent the indoor temperature is to divide by 0.9, that is, $\frac{T_{shade} - T_{out}}{0.9} \cong (T_{in} - T_{out})$. In fact, the column in Table 1 and Table 2 with this label shows that for these experimental measurements, this ratio is always close to unity, and therefore, this is a good approximation for estimating the total temperature differential across the window if more room were available between the window and the shade. The revised calculation of the R-value for the imaginary shade is shown in the column labeled R_s, and it is essentially zero as it should be for an imaginary shade. This same approach was used for temperature measurements when the shade was present to correct for the boundary layer effects.

Are the measured temperature differences in the inside air film shown in Figure 7 (or Figure 8 if the preference is for US units) reasonable? This question is addressed in the Appendix where the temperature differences across different parts of the window, including the air film on the inside and outside of the window, are examined from a theoretical heat transfer perspective. The results presented in Appendix A show that a significant temperature difference between the inside window temperature and the room temperature is expected, and the magnitude of that theoretical temperature difference is similar to that shown in Figure 7.

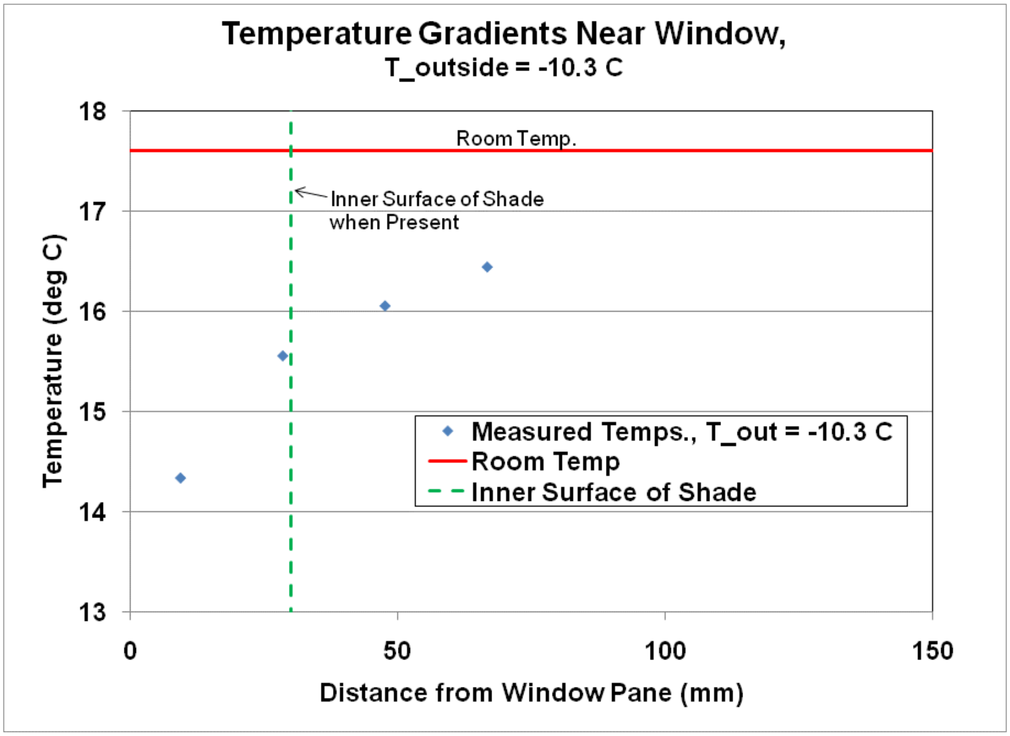

Figure 7. Temperature Gradient in Degrees C Measured Near Window when Shade is Fully Raised using a Stack of T-Sense^{TM} Sensors at an Outdoor Temperature of -10.3˚C.

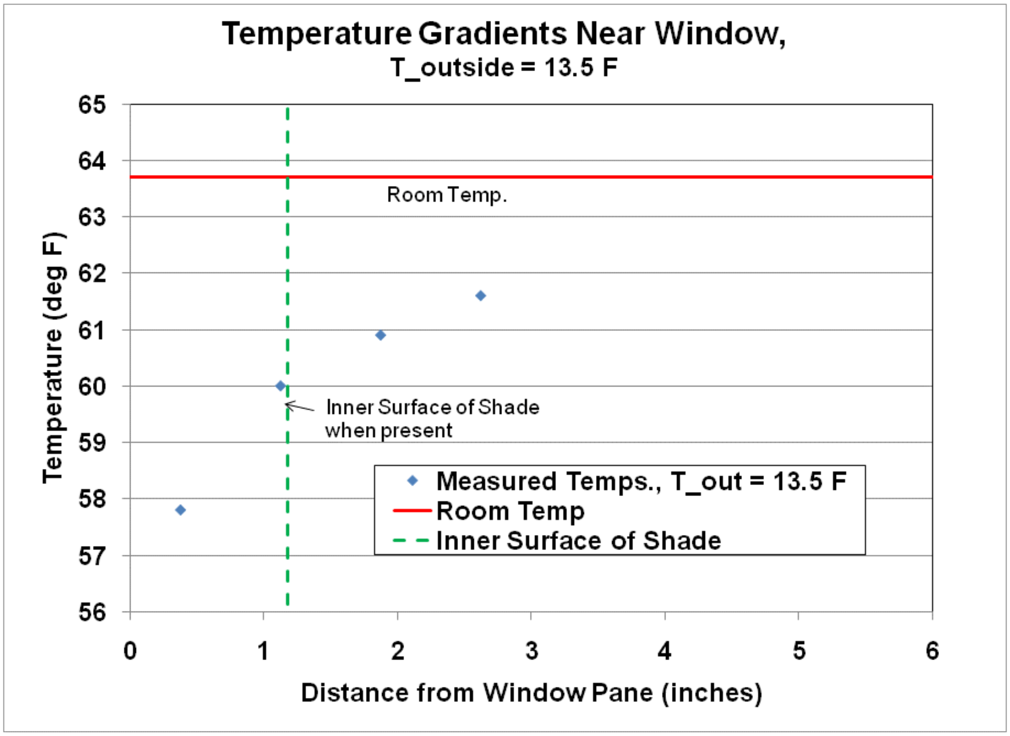

Figure 8. Temperature Gradient in Degrees Fahrenheit Measured Near Window when Shade is Fully Raised using a Stack of T-Sense^{TM} Sensors at an Outdoor Temperature of 13.5˚F.

EXPERIMENTAL RESULTS

Measurements were made on five different windows, two with low solar gain coatings (#1 and #2), and three with high solar gain coatings (#9, #13, and #15). Light-blocking shades were mounted on windows #1, #2, and #9, while light-filtering shades were mounted on windows #13 and #15. For each window/shade combination, tests were conducted with the side seals in place, and with them removed. Data were acquired on a number of days to get a range of outdoor temperatures.

Results for the R-values for the light-filtering shades on two different nominally identical windows, both with the side seals in place and removed, are shown in Figure 9 for R_{SI} (in units of m^2 ˚C/W), and in Figure 10 for R_{US} (in units of ft^2 ˚F h/Btu). Excellent repeatability is shown between results for the two different windows and shades. There is an unexpected trend that shows the thermal resistance values decreasing with decreasing temperatures down to about -6˚C (21˚F), and then more constant values at lower temperatures. This temperature dependence could be due to a variation in the thermal resistance (R-value) for the window with temperature, or a temperature-dependence for the shade. It was assumed that the thermal resistance for the window was independent of temperature, and that the measured variation with temperature was due to an actual variation in the thermal resistance of the shade, likely due to increased convection at greater temperature differentials.

The results in Figure 9 and Figure 10 (same results in two different units of measure) show that the side seals perform as they were designed to perform, dramatically reducing the convective heat transfer from the window to the room. As a result, the R-value is approximately doubled with the addition of the side seals. To specify the numerical R-value for the shades, it is necessary to choose an outdoor temperature at which the measured values should be chosen. There is no measurement standard for determining the thermal resistance of window coverings. The National Fenestration Rating Council (NFRC) also has recommended procedures for determining heat transfer through windows such as NFRC 100-2010, “Procedure for Determining Fenestration Product U-factors. For simulations, they recommend using temperatures as follows: an interior ambient temperature of 21.0˚C (69.8˚F) and an exterior ambient temperature of -18˚C (-0.4˚F). This specified interior temperature is close to what was used in this testing, which averaged about 19˚C (67˚F). However, the exterior temperatures for these tests were greater than that specified above of -18˚C (-0.4˚F). For this work, the temperature at which the R-values were specified was -7˚C (20˚F). At this temperature, the R-values were fairly constant, and this is a more representative average winter-time temperature in the U.S. than the NFRC value of -18˚C (-0.4˚F).

At an outdoor temperature of -7˚C (20˚F), the R-value for the light-filtering shades without side seals was $R_{SI} = 0.10$ ($R_{US} = 0.57$), while the addition of the side seals more than doubled the R-value to $R_{SI} = 0.21$ ($R_{US} = 1.2$). At higher outdoor temperatures, the R-values were significantly greater; that is, the shades were better insulators at higher outdoor temperatures.

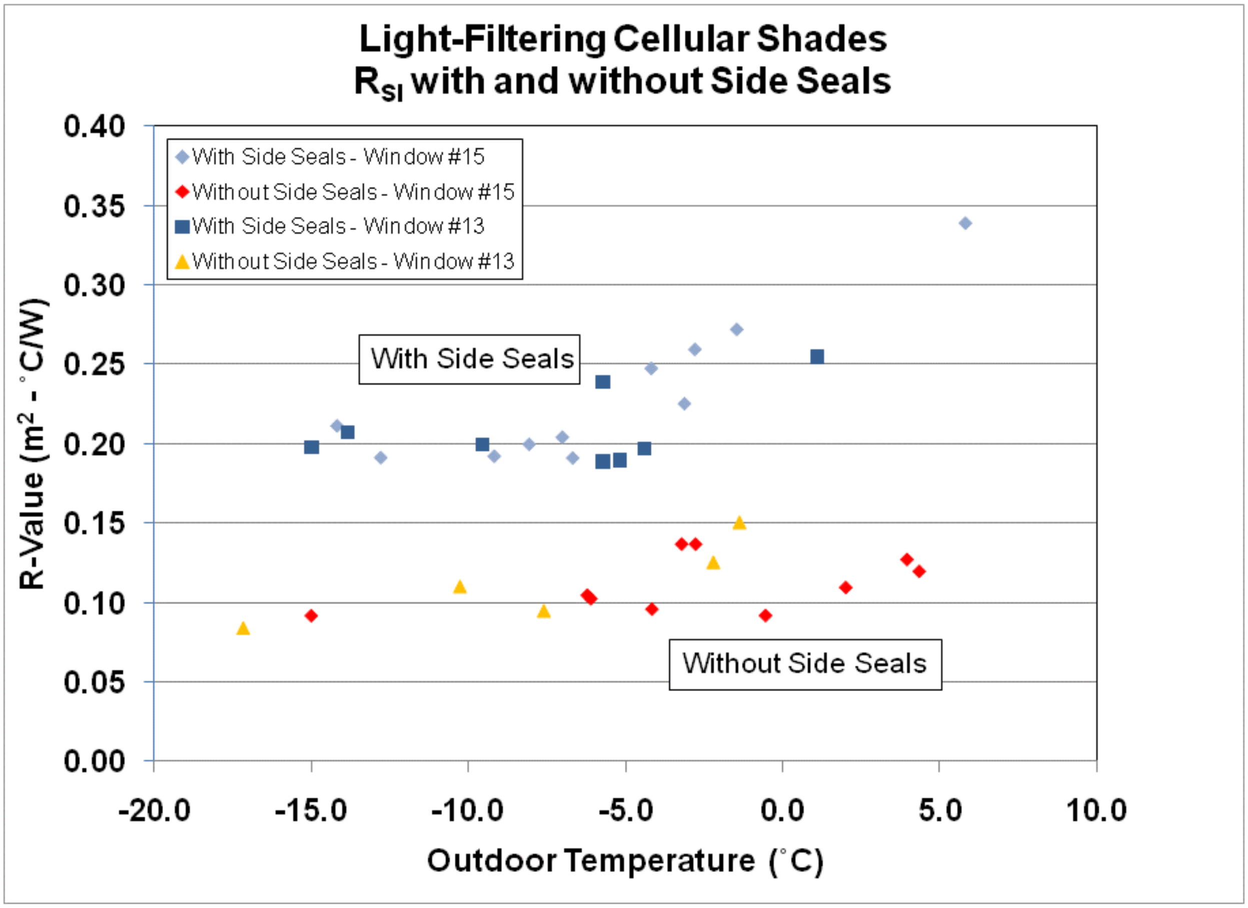

Figure 9. R_{SI} Measured for Light-Filtering Shades for Two Nominally Identical Windows, both with and without the Side Seals.

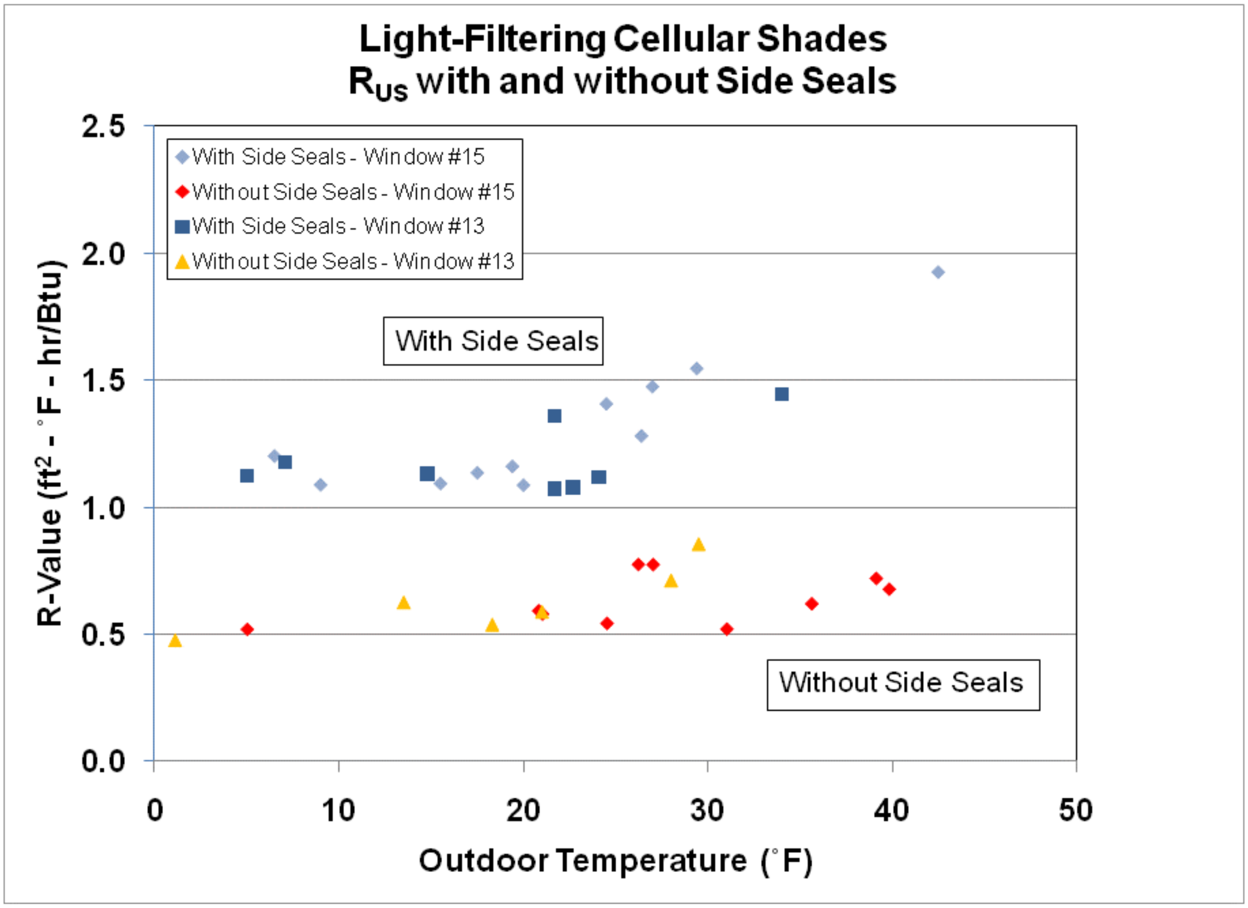

Figure 10. R_{US} Measured for Light-Filtering Shades for Two Nominally Identical Windows, both with and without the Side Seals.

Thermal resistance values for the light-blocking shades were made, both with and without side seals, on three different windows, #1, #2, and #9, where the first two were low solar gain windows and the third was a high solar gain window. Results for R-value in metric units (R_{SI}) are shown in Figure 11, and in US units (R_{US}) are shown in Figure 12. Repeatability for measured R-values without the side seals was excellent between the three windows. R-values with the side seals showed more scatter, presumably due to differences in the fit for the side seals. For the light-blocking shades without side seals, the R-value at an outdoor temperature of -7˚C (20˚F) was R_{SI} = 0.13 (R_{US} = 0.74), while adding the side seals more than doubled this value to R_{SI} = 0.35 (R_{US} = 2.0). Thus, the light-blocking shades were significantly better insulators than the light-filtering shades, and adding the side seals almost tripled the R-values for the light-blocking shades.

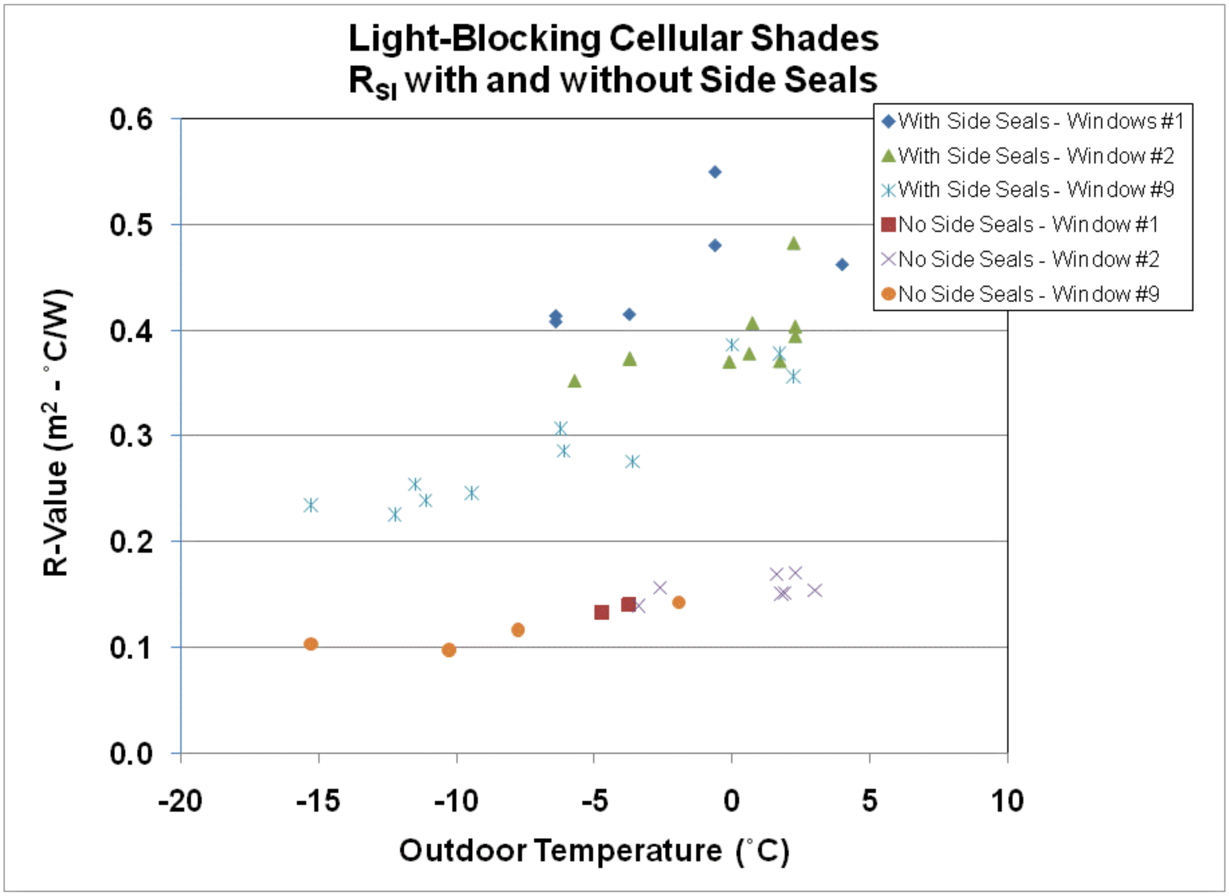

Figure 11. R_{SI} Measured for Three Different Windows (Two Low Solar Gain, #1 and #2, One High Solar Gain, #9) for Light-Blocking Shades, both with and without Side Seals.

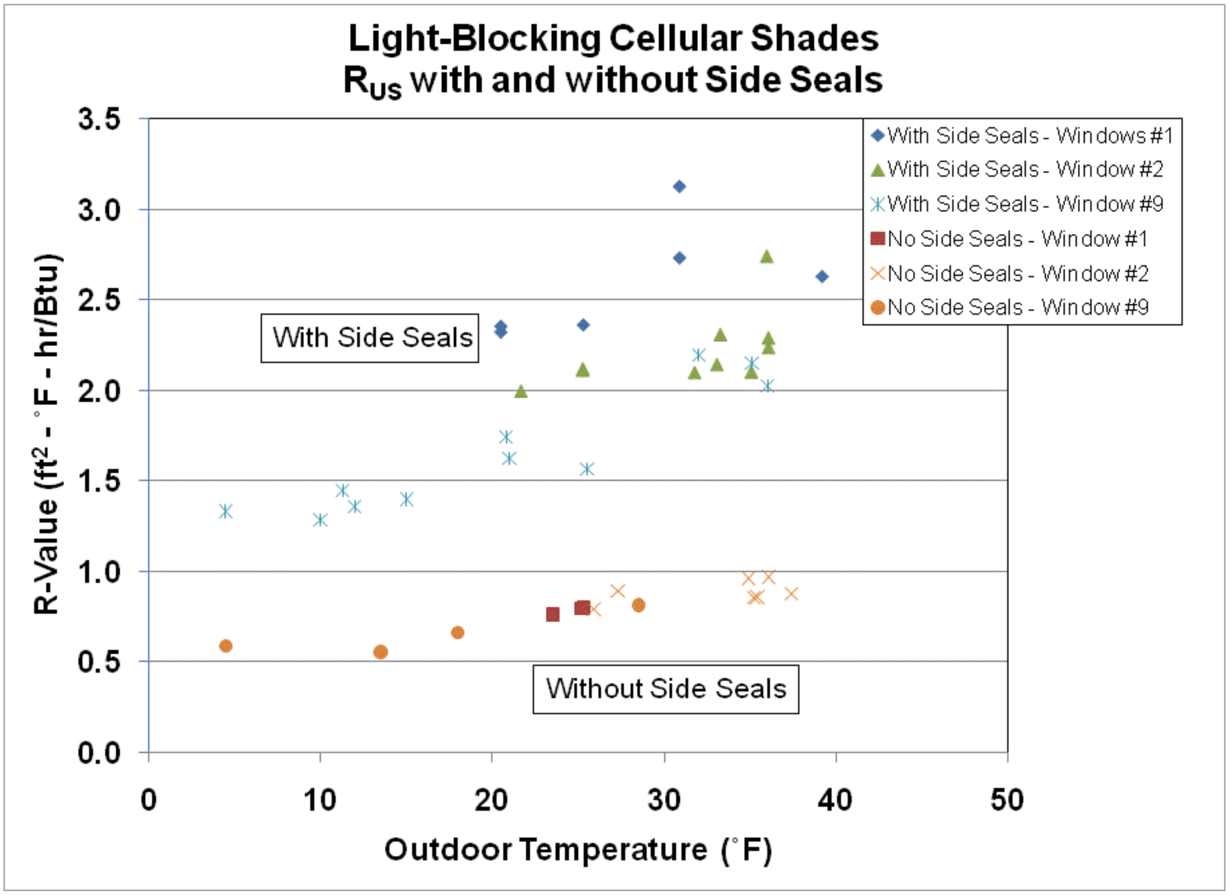

Figure 12. R_{US} Measured for Three Different Windows (Two Low Solar Gain, #1 and #2, One High Solar Gain, #9) for Light-Blocking Shades, both with and without Side Seals.

DISCUSSION

From the test results above, the light-blocking shades are clearly superior to the light filtering shades in terms in insulating properties, having roughly 50% higher R-values. However, the choice between these two types is often based on color choice, or the desire for the amount of light to allow into the room during the daytime, rather than insulating properties. Another factor to consider is that the light-blocking shades are apparently made by adding a layer of aluminum foil to the blinds. This makes the blinds stiffer to raise and lower, with lowering the shade often requiring use of the second hand to pull the shade to the completely closed page. Another interesting characteristic of the light-blocking shades is that they take a few minutes to completely straighten out all the folds, and in the process of straightening out, they crackle for five minutes or so. The light-blocking shades are more expensive than the light-filtering shades, $121 versus $93 for the size shades tested (without side seals), or 30% more.

The side seals were very effective in reducing the convective flow across the windows. The air flow is the reverse of a hot radiator, and is shown in Figure 13. This airflow pattern is supported by the infrared thermal image shown in Figure 14 that shows warmer colors toward the upper part of the window. Further, the average temperatures measured by the sensors near the midline of the top window pane were 1.8˚C (3.2˚F) higher than temperatures measured near the midline of the bottom window pane. This reduction in convective airflow resulted in increasing the R-value for the cellular shades by a factor of two or more. It also increased the time required to install the shades by about a factor of two. Further, adding the side seals increased the cost of the shades by $42 in the size tested.

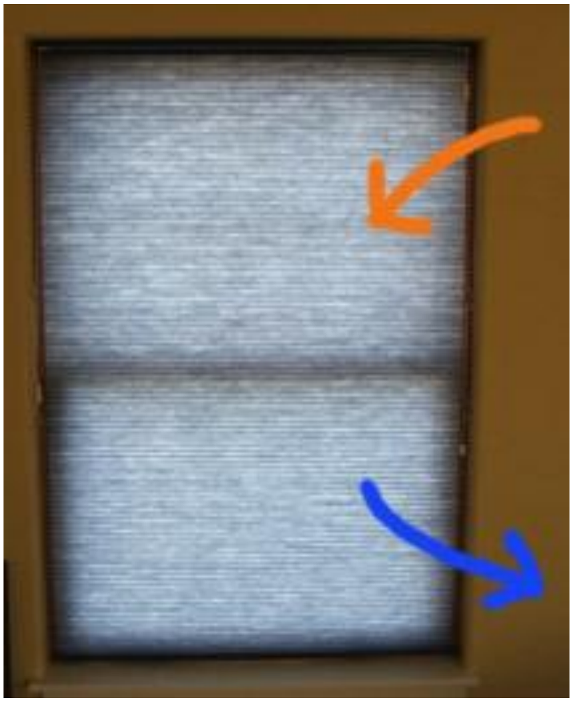

Figure 13. Convective Airflow across Window from Top to Bottom with Cold Exterior Temperatures, the Reverse of the Flow across a Hot Radiator.

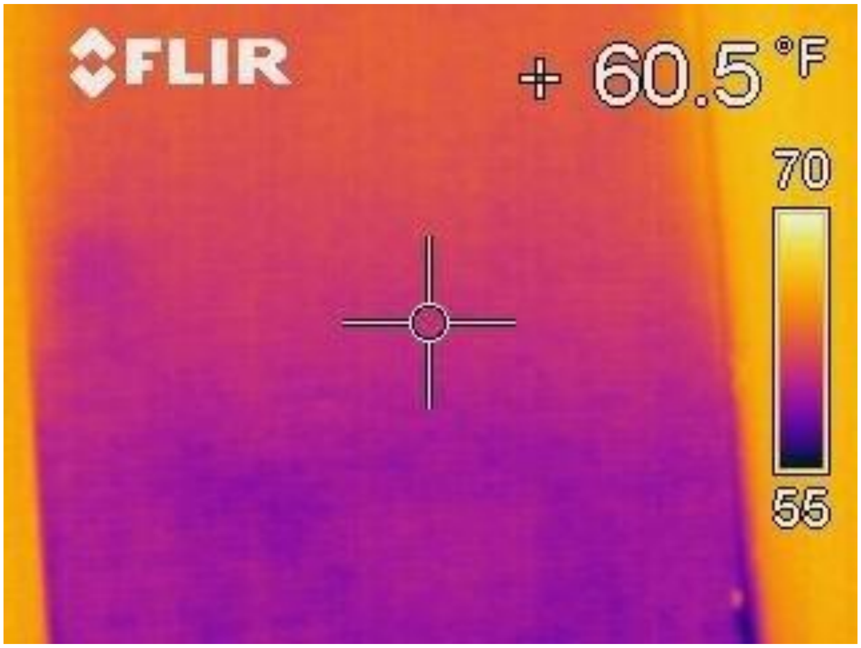

Figure 14. Infrared Thermal Image of Window from Previous Figure Showing Warm Air at the Top, Cooler Air toward the Bottom, under Conditions of Cold Outside Air.

These prices for cellular shades are too high to justify their purchase based solely on energy savings when they are used with low-e, triple pane windows. However, many people like to use window coverings for privacy, style, or to avoid sun damage to furnishings, and these cellular shades, especially with the side seals, offer a significant boost in insulating value for the window/shade combination. Windows in new homes in cooler climates in the United States require the thermal conductivity to be lower than 2.0 W/m^2 ˚C (0.35 Btu/h ft^2 ˚F), corresponding to a minimum R_{SI} of 0.5 (R_{US} = 2.9). Thus, the R-values of these shades can be significant relative to the R-value for the windows alone, increasing the R-value for the combination of window plus shade by up to 70% (for light-blocking with side seals) over a window alone that meets the new minimum code requirements for new construction. For older windows, the improvement would be even more significant. For a single-pane window with an R_{SI} of about 0.16 (R_{US} = 0.9), the combination of the window plus shade would give an R-value of up to 422% that of the window alone (for the light-blocking shade with side seals). In addition to the energy savings, these shades with the side seals increase the comfort level in the house, reducing radiation losses to the cool window surfaces, and reducing convective air currents near the windows.

How do the results reported here compare with previous results reported in the Steven Winter Associates report? Their results were only for the light-blocking shades, so comparisons should be limited to the corresponding shades tested here. Steven Winter Associates reported different results for R-values for the shades tested on single pane windows with an exterior storm window compared to results for newer low-e, double pane windows, while the shades should have the same R-value. Averaging their results for the two windows, without the side seals R_{SI} = 0.20 (R_{US} = 1.1), while with the side seals they report R_{SI} = 0.60 (R_{US} = 3.4). The corresponding results reported here were R_{SI} = 0.13 (R_{US} = 0.74) without side seals, and R_{SI} = 0.35 (R_{US} = 2.0) with side seals. So the R-values results reported here are significantly lower than those reported by Steven Winter Associates, with the results as shown in Table 3 in SI units and Table 4 in US units.

Table 3. Comparison of R_{SI} for Cellular Shades with and without Side Seals as Measured by Steven Winter Associates, LLC and in this Report.

	R_{SI}, Steven Winter, 0.8˚C	R_{SI}, This report, -7˚C
Shades without side seals	0.20	0.13
Shades with side seals	0.60	0.35

Table 4. Comparison of R_{US} for Cellular Shades with and without Side Seals as Measured by Steven Winter Associates, LLC and in this Report.

	R_{US}, Steven Winter, 33˚F	R_{US}, This report, 20˚F
Shades without side seals	1.1	0.74
Shades with side seals	3.4	2.0

The differences in reported R-values may be traced to two factors. First, Steven Winter Associates did not correct for the boundary layer effect discussed in the TEST PROCEDURE section above. Secondly, the Steven Winter data are for a higher temperature than the -7˚C (20˚F) "standard" temperature chosen for these results. Assuming that the data taken by Steven Winter Associates were roughly the same distance from the window surface as the results reported here, then their data may be roughly corrected by subtracting out the R-value that they would have measured for an imaginary shade using their approach, as shown in Table 5 in R_{SI} units, and in Table 6 in R_{US} units. This would mean that 0.06 should be subtracted from their R_{SI} values, and 0.34 from their R_{US} values. The temperature range for data taken by Steven Winter Associates was quite narrow, but data are shown in this report for a range of temperatures. Therefore, it is possible to examine results shown in Figures 11 and 12 corresponding to their average outdoor temperature of 0.8˚C (33˚F). In Tables 5 and 6 (for R_{SI} and R_{US} units, respectively), data from this report are shown for the same temperatures as those used by Steven Winter Associates. Further, the Steven Winter data have been corrected for the boundary layer effect. Within the scatter of the data, the Steven Winter data, after correction for the boundary layer error, agree fairly well with those reported here. Before correction, the Steven Winter data appear to be biased toward higher R-values than the "true" due to the boundary layer effect in their measured temperatures.

Table 5. Comparison of R_{SI} for Cellular Shades with and without Side Seals as Measured by Steven Winter Associates and Corrected for Boundary Layer Effect, and in this Report at the Same Test Temperature (0.8˚C).

	R_{SI} ***corrected***, Steven Winter, 0.8˚C	R_{SI}, This report, 0.8˚C
Shades without side seals	0.14	0.16
Shades with side seals	0.54	0.43

Table 6. Comparison of R_{US} for Cellular Shades with and without Side Seals as Measured by Steven Winter Associates and Corrected for Boundary Layer Effect, and in this Report at the Same Test Temperature (33˚F).

	R_{US} corrected, Steven Winter, 33˚F	R_{US}, This report, 33˚F
Shades without side seals	0.80	0.91
Shades with side seals	3.1	2.4

A disadvantage of insulating window coverings of any type is that they lower the inside glass temperature during the heating season, increasing the chances of condensing water on the window surface. The addition of the side seals reduces the window temperature more than the shades without side seals, but it also reduces the convective airflow across the surface. The reduced window temperatures tend to increase condensation, but the reduced convective airflow should reduce condensation. Thus, the moisture condensation could be increased or decreased by the presence of the side seals. The effect of side seals on condensation rates was not studied in this work. Condensation temperatures may be calculated as a function of interior relative humidity by using the calculator at Reference 3. A way to avoid the condensation issues is to use shutters outside the house rather than inside. Opening and closing external window coverings can be an issue in areas with snow and ice, and usually requires more effort than closing inside shades.

CONCLUSIONS

The addition of side seals to cellular shades increases the insulating values of the shades by a factor between two and three. The side seals also reduce light leakage around the edges of the shades. Light-blocking cellular shades have significantly greater insulating values than light-filtering shades, although the choice between the two is usually based on color choice and desire for amount of light to penetrate the shades rather than insulating characteristics.

An outside temperature of -7˚C (20˚F) was chosen as a "standard" temperature at which to quantify the thermal resistance (R-value) for the shades. Indoor temperatures were maintained at about 19˚C (67˚F). At these conditions, the R-value for the light-filtering shades without side seals was $R_{SI} = 0.10$ ($R_{US} = 0.57$), while the addition of the side seals more than doubled the R-value to $R_{SI} = 0.21$ ($R_{US} = 1.2$). For the light-blocking shades without side seals, the R-value at an outdoor temperature of -7˚C (20˚F) was $R_{SI} = 0.13$ ($R_{US} = 0.74$), while adding the side seals almost tripled this value to $R_{SI} = 0.35$ ($R_{US} = 2.0$). At higher outdoor temperatures, the R-values increase dramatically. These insulating values are significant compared to the insulating values for windows alone, so the addition of this type of window coverings can significantly reduce heat losses in a home. During the cooling season, the shades can block most of the thermal energy that would enter the home through the windows, although this effect was not studied for this report.

ACKNOWLEDGEMENTS

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Reference 2.
http://blindalley.com/portfolios/hunterdouglas/portfolioslarge/duetteenergyefficiency.html)

Reference 3. http://www.builditsolar.com/References/Calculators/Window/condensation.html

APPENDIX – DETAILED ANALYSIS OF WINDOW HEAT LOSSES

As discussed in the section above titled TEST PROCEDURE, a previously published approach to measuring the thermal resistance of shades gives a non-zero R-value even when no shade is present. In this report, an approach has been developed to process temperature measurements in such a way that the thermal resistance is computed equal to the correct value of zero if the temperature measurements are taken when no shade is present. The approach developed as described above is based on experimental measurements with no shade present. The purpose of this Appendix is to analyze heat losses and predicted temperatures across a triple-pane, low-emissivity ("low-e") window like those used in these tests, but based on published heat transfer equations rather than the experimental results presented above. The theoretical results are compared to the measured results presented above.

For this analysis, the triple pane window surfaces are numbered following the standard convention of numbering the outside surface of the outermost pane as surface #1, the inner surface of the outermost pane as surface #2, the outer surface of the middle pane as surface #3, the inner surface of the middle pane as surface #4, the outer surface of the inner pane as surface #5, and the inner surface of the inner pane as surface #6. The outside free air well away from the window is labeled as #0, and the inside free air well away from the window is labeled as #7. The surfaces are shown above the diagram below in Figure A-1, and the corresponding temperatures are shown below the diagram.

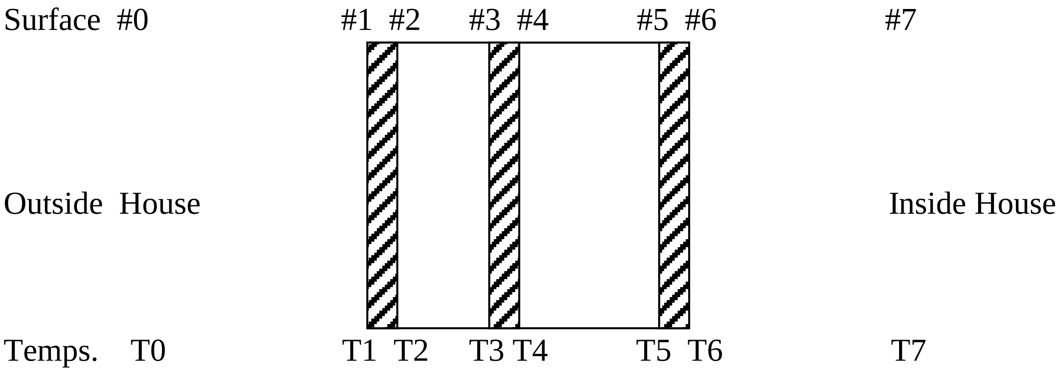

Figure A-1. Schematic for Triple-Pane Window Surfaces and Temperatures.

For the Pella Designer double-hung windows used for these tests, the glass pane thicknesses were estimated to be about 3 mm (1/8"), the air film between the outer two panes about 8 mm (5/16") thick, and the air film between the inner two panes about 25.4 mm (1") thick. Only the outer two panes are in an insulated glass unit, while the inner pane is separately mounted and sealed so that mini-blinds may be inserted into the larger space. These windows were used at "high altitude," and therefore were filled with air and equipped with capillary tubes rather than being sealed with argon to avoid glass breakage associated with moving sealed windows from a low altitude manufacturing site to a high altitude home site.

Refer to Figure A-1 above to follow the heat transfer from inside the house to outside the hosue. The heat fluxes through the triple-pane windows may be summarized as follows: the natural convection in the air films between the inside free air, surface #7, and the innermost glass surface, #6, called $\dot{Q}_{76}$, the conduction across the innermost glass plane, $\dot{Q}_{65}$, the conduction, convection, and radiation across the air gap between the inner and middle glass panes, $\dot{Q}_{54}$, the conduction across the middle glass plane, $\dot{Q}_{43}$, the conduction, convection, and radiation across the air gap between the middle and outer glass panes, $\dot{Q}_{32}$, the conduction across the outermost glass plane, $\dot{Q}_{21}$, and the natural convection in the air films between the outermost glass surface, #1 and the outside free air, surface #0, and, called $\dot{Q}_{10}$. If the window is assumed to be large so that the heat fluxes are from one section to the next, and not out the sides, then these heat fluxes are all equal.

The heat fluxes may be quantified as follows. The natural convection heat transfer in the air film between the inside free air and the innermost glass surface, $\dot{Q}_{76}$,

$$\dot{Q}_{76} = h\, A\, \Delta T_{76} \qquad (A1)$$

where:
$\dot{Q}_{76} =$ total heat flux from surface #7 to #6
h = convective heat transfer parameter
A = area = 1.513 m^2
ΔT_{76} = temperature difference between surfaces #7 and #6 (inside free air and inner window surface)
The heat transfer between the room air and the inner window surface may be assumed to be driven by natural convection, and the heat transfer coefficient, h, is given by (for example, Ref. A-1),

$$h = 1.8\, \Delta T_{76}^{0.25} \qquad (A2)$$

The heat flux in the air film on the outside of the window, $\dot{Q}_{10}$, may be taken as the same form as the heat flux on the inside air film in the case of no forced convection due to wind, which is the condition under which window heat fluxes are measured for certification.

The heat flux through the glass window panes can be estimated as heat conduction, so, for example, $\dot{Q}_{65}$ is computed as,

$$\dot{Q}_{65} = U_{glass}\, A\, \Delta T_{65} \qquad (A3)$$

where:
U_{glass} = thermal conductivity of window glass

The thermal conductivity of window glass is given in the Engineering Tool Box at Reference A-2 as 0.96 W/(m K), so for a 3 mm thick piece of window glass the U value becomes 0.00288 W/(m^2 K). The area A is the same as given under Eq. A1, and that same area is used in the equations below. So Eq. A3 becomes,

$$\dot{Q}_{65} = 0.00288\, A\, \Delta T_{65} \quad (A4)$$

The two other glass panes are assumed to be the same thickness, so Eq. A4 is used for $\dot{Q}_{43}$ with T_{43} substituted for T_{76}, and for , $\dot{Q}_{21}$ with T_{21} substituted for T_{76}.

The heat flux between the outer two panes of glass may be treated as a gas conduction problem rather than a convection problem because of the narrow space between the outer two window panes, surfaces #3 and #4, estimated to be a gap of 8 mm (5/16"). The justification for treating it as conduction rather than convection is given by Bird et al. (Ref. A-3) and by R. Shankar Subramanian (Ref. A-4). Thus, the heat flux through the air gap between the outer two panes of glass, $\dot{Q}_{21}$, takes the same form as the heat conduction through the glass panes, except with a much lower thermal conductivity,

$$\dot{Q}_{21} = U_{air}\, A\, \Delta T_{21} \quad (A5)$$

where:
U_{air} = thermal conductivity of air
The thermal conductivity of air at 10˚C is 0.0250 W/(m K) according to the The Engineering ToolBox, at Reference A-5. For the estimated gap of 8 mm (5/16") between surfaces #3 and #4, the thermal conductivity becomes 3.125 W/(m^2 K). Thus, Eq. A5 becomes,

$$\dot{Q}_{21} = 3.125\, A\, \Delta T_{21} \quad (A6)$$

The only remaining heat transfer quantity that needs to be defined is the heat flux through the air gap between the inner and middle window panes, or surfaces #4 and #5 in Fig. A-1. The gap estimated to be 25 mm (1") is too large to assume that the heat transfer can be computed as simply heat conduction, but it is too small to easily treat it as natural convection. Figure A-2 in SI units and Figure A-3 in American units (from Cardinal Glass catalog data) show that the heat transfer rate for a 25 mm (1") gap is similar to, but maybe slightly greater than, the heat transfer rate for the 8 mm (5/16") that is given by Eq. A6. Therefore, for this analysis, the heat transfer rate for $\dot{Q}_{54}$ was set equal to $\dot{Q}_{21}$ given in Eq. A6. This is the equivalent to saying that the same value was used for U_{air} for both these cases, even though the air gap was different, based on results shown in Figs. A-2 or A-3.

Now expressions have been given above for all the heat fluxes through the window system shown in Fig. A-1, but the temperature drops in each section are unknown. Some constraints must be set to solve the simultaneous equations for heat transfer. First, the conditions of interest are for those conditions where the R-values have been determined, and those "standard" conditions are an indoor temperature of 19.4˚C (67˚F), and an outdoor temperature of -6.7˚C (20˚F), or a total differential temperature of 26.1˚C (47˚F). As stated above, it is assumed that the heat transfer rates through each section shown in Fig. A-1 are the same, so that heat transfer to the edges of the window are ignored. This means that,

$$\dot{Q}_{76} = \dot{Q}_{65} = \dot{Q}_{54} = \dot{Q}_{43} = \dot{Q}_{32} = \dot{Q}_{21} = \dot{Q}_{10} \quad (A7)$$

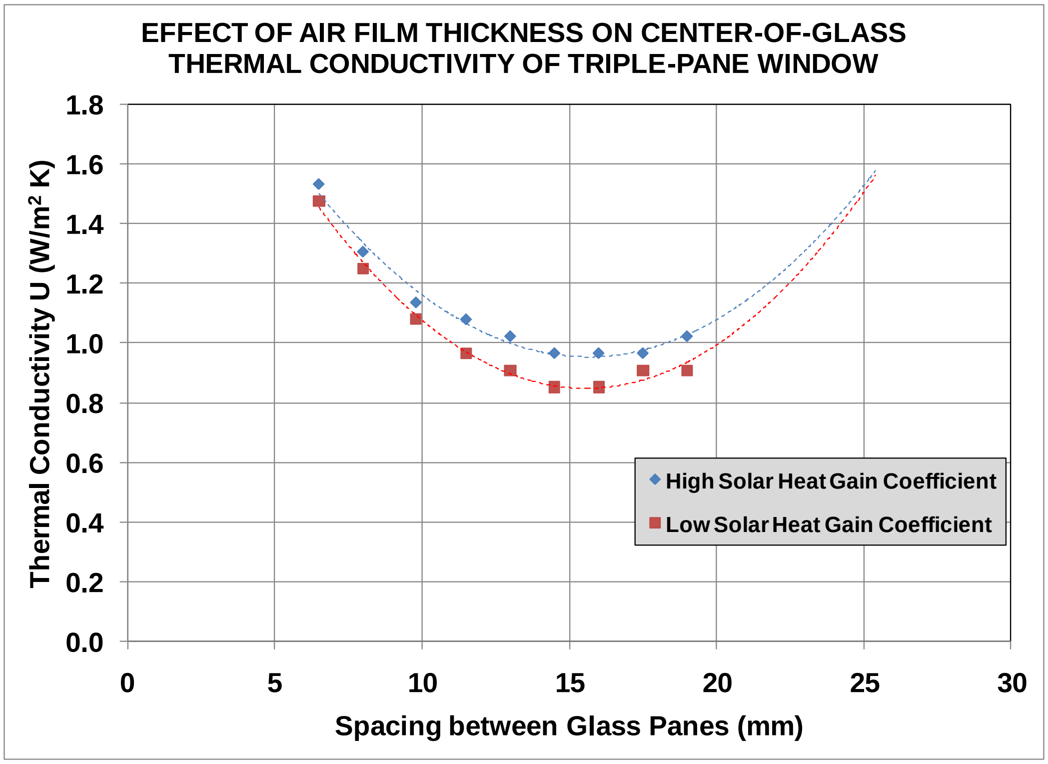

Figure A-2. Effect of Air Film Thickness on the Thermal Conductivity of Triple-Pane Windows in SI Units (from Cardinal Glass catalog data).

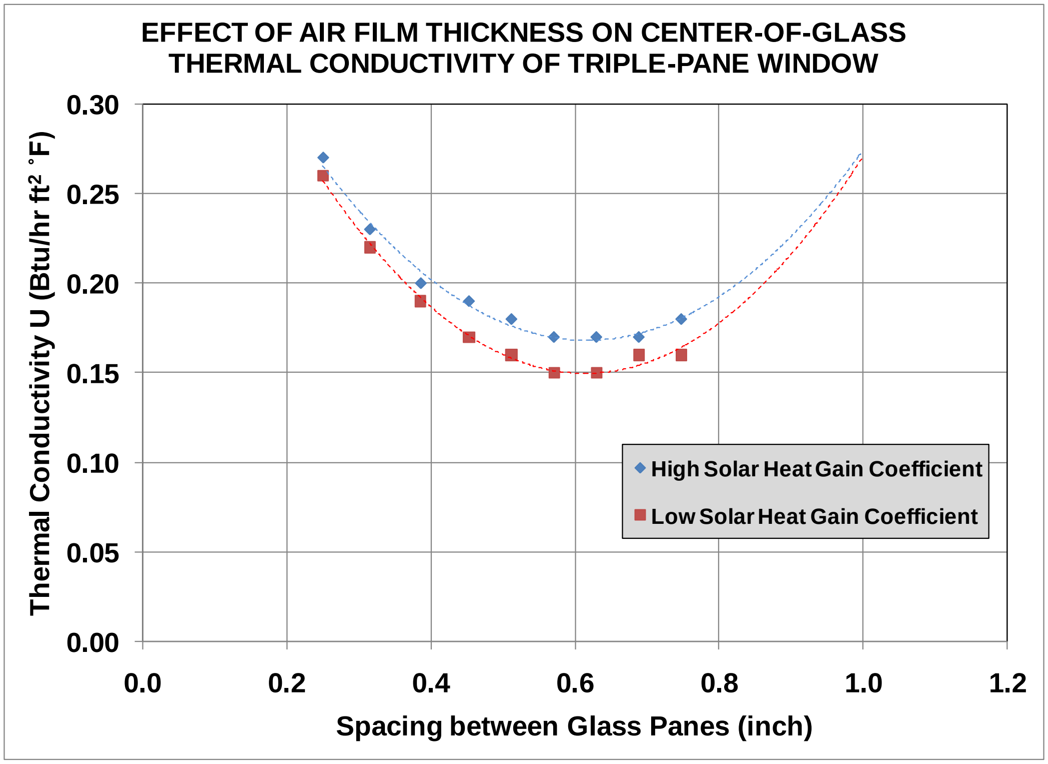

Figure A-3. Effect of Air Film Thickness on the Thermal Conductivity of Triple-Pane Windows in American Units (from Cardinal Glass catalog data).

It is further known that the temperature differentials must sum to the total temperature difference of 26.1˚C (47˚F), or in SI units,

$$T_{76} + T_{65} + T_{54} + T_{43} + T_{32} + T_{21} + T_{10} = 26.1 \qquad (A8)$$

These constraints are then sufficient to solve the simultaneous equations A2, A4, and A6. The results are as follows:

$$T_{76} = T_{10} = 6.7^{\circ}C \qquad (A9)$$

$$T_{65} = T_{43} = T_{21} = 0.06^{\circ}C \qquad (A10)$$

$$T_{54} = T_{32} = 6.2^{\circ}C \qquad (A9)$$

The following conclusions may be drawn from these results:

- The thermal resistance of the window glass is negligible compared to the thermal resistance of the air films.

- The air films between the air-filled sealed glass window panes provide about the same thermal resistance as the air films on the inside and outside of the window assembly in cases where the wind is not blowing and adding to the convective heat transfer rate.

- The previously presented measured temperature gradients from Fig. 7 and repeated (for convenience) as Fig. A-4 below show a total temperature gradient from the inner window glass temperature to the room temperature of about 4.7˚C (for a total temperature difference between indoor and outdoor temperatures of 28˚C) based on extrapolating the results in Fig. A-4 to the window surface. This is a reasonable measured value compared to the theoretical temperature difference derived independently of 6.7˚C presented in Eq. A9 above. This result supports the concept original to this report that measurements of the air temperature close to the glass surface when a shade is down cannot be used as an approximation of the ambient room temperature when the shade is raised, and cannot be used to estimate the R-value for the shade unless a procedure is developed to compensate for those temperature differences.

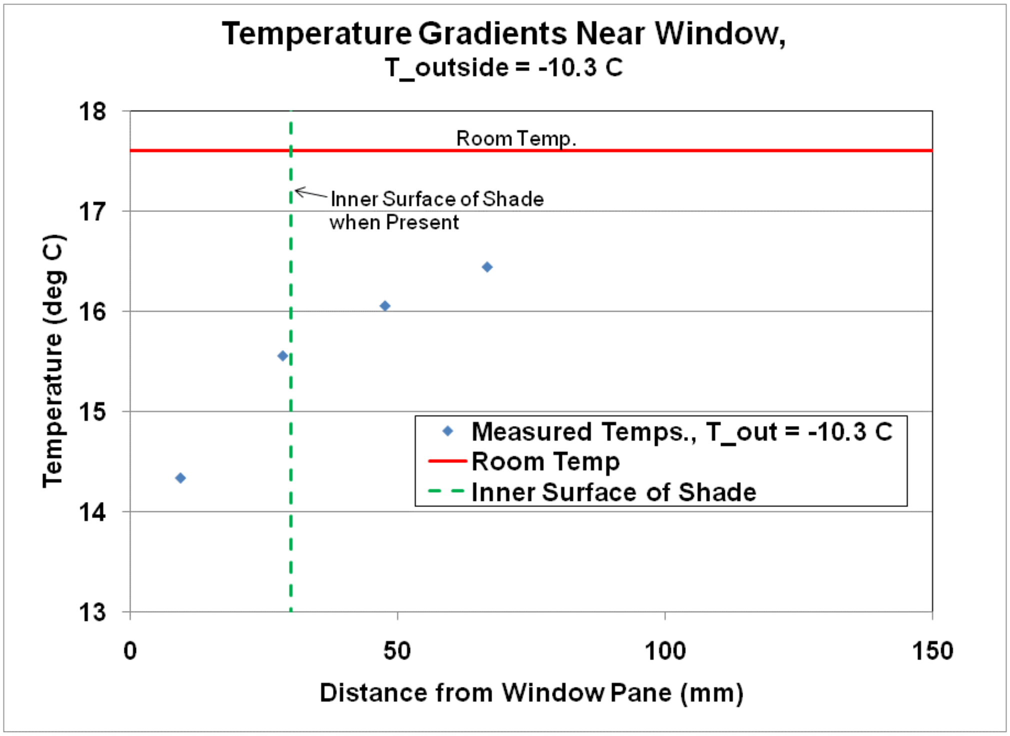

Figure A-4. Temperature Gradient in Degrees C Measured Near Window when Shade is Fully Raised using a Stack of T-Sense^{TM} Sensors at an Outdoor Temperature of -10.3°C.

REFERENCES FOR APPENDIX

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